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RESEARCH REPORT No. EM-127

Back Scattering From a Finite Cone

JOSEPH B. KELLER

Contract No. AF19(604)1717

FEBRUARY, 1959

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The research reported in this document has been sponsored by the Electronics Research Directorate of the Air Force Cambridge Research Center, Air Research and Development Command. The publication of this report does not necessarily constitute approval by the Air Force of the findings or conclusions contained herein.

Contract No. AF 19(604)1717

February, 1959

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Abstract*

Back scattering is calculated for an acoustic wave incident on a hard or soft finite cone, and an electromagnetic wave incident on a perfectly conducting finite cone. Two shapes of cone are treated, one with a flat base and the other with a rounded base. The calculation is based on the geometrical theory of diffraction. Therefore it is valid for wavelengths as large as the cone dimensions or smaller. Graphs of the back scattering cross-section versus cone angle and versus wavelength are given for axial incidence on the flat-based cone. Suggestions for shaping an object to minimize its back scattering are also included.

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*Some of these results were contained in a report entitled "Radar return from metallic objects" written in January, 1958, when the author was a consultant to the General Electric Co., Missiles and Ordnance Systems Dept. Aerodynamics Lab., Communications Section. Most of the other results were contained in a paper with the present title read at the Washington meeting of U.R.S.I. in May, 1958.

1. Introduction

The back scattering from a finite cone is calculated in this report by means of the geometrical theory of diffraction[1], [2] Three different physical problems are considered. One is that of an acoustic wave incident upon a rigid cone. The second is that of an acoustic wave incident upon a perfectly soft (pressure-release) cone. The third, and perhaps most important, is that of an electromagnetic wave incident upon a perfectly conducting cone. In all cases two different types of cones are treated. One is a truncated right circular cone with a flat base. The other has a rounded base which is a portion of a sphere. The sphere and cone join smoothly, with no sharp edge. For simplicity the incident wave is assumed to be plane and only the back-scattered field is found, although both of these limitations could easily be removed.

The theory employed here represents the back-scattered field as a superposition of fields on various rays. Some of these are the ordinary optical rays which are reflected from the cone and the others are diffracted rays. In the next section the various rays are described and a qualitative description of the back scattering process is given. In Sections 3-5 the quantitative results are derived and examined. Graphs of the back scattering cross section are also presented. In the conclusion, Section 6, suggestions are made about shaping an object to minimize its back-scattering cross section.

Most of the previous theoretical results on back scattering from cones have concerned semi-infinite cones. For such cones the acoustic diffraction problem was solved exactly and explicitly by H. S. Carslaw[3] and the electromagnetic problem by W. W. Hansen and L. I. Schiff[4]. Their solutions were given as infinite series which were difficult to evaluate. For the case of axial incidence, the back scattered fields

were evaluated for small angle and large angle cones by C. E. Schensted[5], K. M. Siegel, J.W. Crispin and C. E. Schensted[6] and L. B. Felsen[7], [8]. For off axial incidence on small angle cones, they were evaluated by L. B. Felsen[9]. For axial incidence, Felsen[10] has also evaluated the back scattered fields approximately for cones of any angle. Another approximate result for the back scattered field was found by R. C. Spenser[11] using the Kirchhoff method. All of these results pertain to the field diffracted from the tip and yield what we call the tip diffraction coefficient. As we shall see, this field is not important for the flat-based cone, but it is important for the round-based cone.

The kirchhoff method has been applied to the finite cone by K. M. Siegel, et al[12]. Siegel[13] has also treated the case of axial incidence on the flat-based finite cone by a variant of our method. However, his result is incorrect because of an error in his formula for the field scattered from a wedge.

2. Qualitative description

Let us consider a plane wave incident upon a finite cone with a flat base. We denote the half-angle of the cone by γ and the radius of the base by a. (See Figure 1.) Let ϕ denote the angle between the incident rays and the axis of the cone, with the range of ϕ given by $0 \leq \phi \leq \pi$. The extreme values $\phi = 0$ and $\phi = \pi$ denote incidence along the axis, upon

the tip and base respectively. When $\phi = \pi$ the incident rays hit the base normally and therefore produce specularly reflected rays which return to the source. When $\phi = \frac{\pi}{2} - \gamma$ the incident rays are normal to the curved surface of the cone and also give rise to specularly reflected rays which return to the source. For all other values of ϕ no specularly reflected rays are returned to the source. As a consequence the back scattering is strongest at $\phi = \pi$ and $\phi = \frac{\pi}{2} - \gamma$.

When $\phi \neq \pi, \frac{\pi}{2} - \gamma$ the only back scattered rays are diffracted ones. The field on a ray diffracted from the tip is proportional to k^{-1}, that on a ray diffracted from the edge is proportional to $k^{-1/2}$, and that on a surface diffracted ray decreases exponentially with k. Therefore for large k, or more precisely for large ka, the edge diffracted rays are most important, the tip diffracted rays are next and the surface rays least. Rays doubly diffracted at edges also have fields proportional to k^{-1} so they are equal in importance to tip diffracted rays. When $\phi = 0$ or π the edge diffracted rays have a caustic on the axis, so their field there is multiplied by $k^{1/2}$. In this case the singly diffracted edge rays contribute a field proportional to k^{0} and the doubly diffracted ones a field proportional to $k^{-1/2}$. Thus when $\phi = 0$ the doubly diffracted edge rays are more important than the singly diffracted tip ray. In addition the amplitude of the singly diffracted edge field is independent of k, just like the incident field.

When ϕ lies in the interval $0 < \phi < \gamma$ or the interval $\frac{\pi}{2} < \phi < \pi$, two rays singly diffracted at the edge are returned to the source. Therefore in these ranges the back scattered field will be an oscillatory function of ka, due to interference between these two rays. When ϕ lies in the interval $\gamma < \phi < \frac{\pi}{2}$ only one ray singly diffracted at the edge returns to

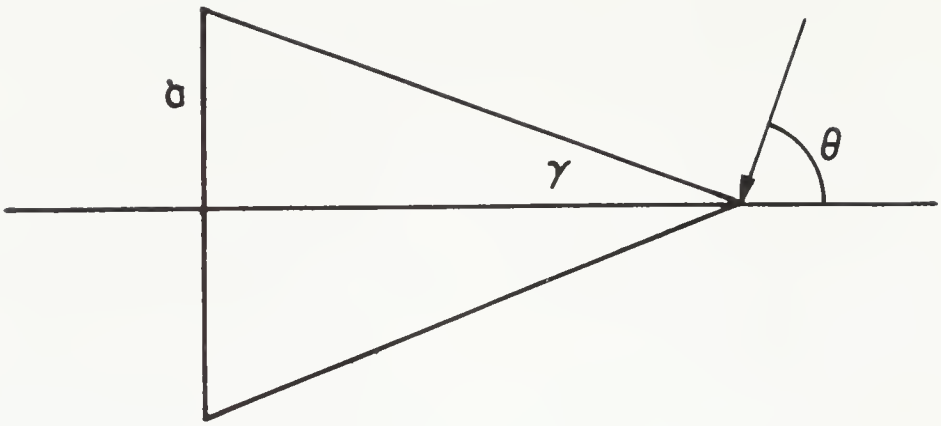

Figure 1.

Cross section of a finite cone of half-angle γ with a flat base of radius a. The tip of the cone is the origin of a polar coordinate system and the angle ϕ is measured from the axis.

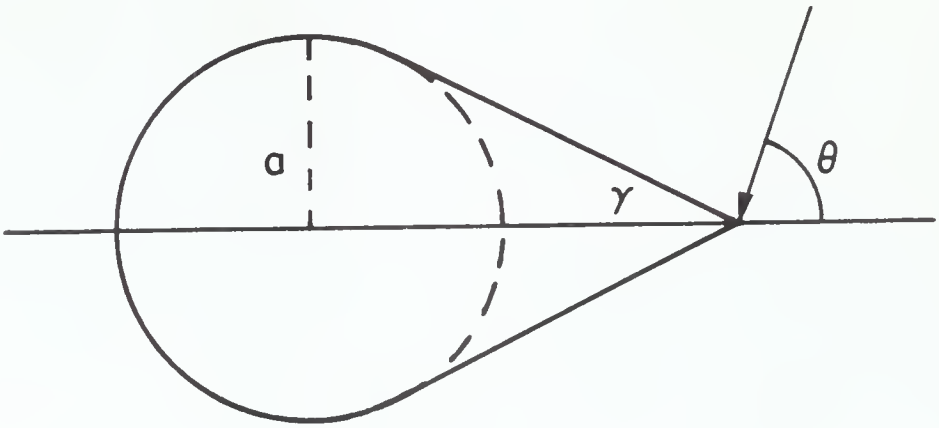

Figure 2.

Cross section of a finite cone of half-angle γ with a spherical base of radius a. The cone is tangential to the sphere where they join.

the source. Therefore the field will not oscillate as ka varies, except for a small oscillation due to interference with a doubly diffracted ray. In all these cases, the amplitude of the field will be proportional to $(ka)^{-1/2}$.

Let us now consider the same problem for the finite cone of Figure 2. This cone has a spherical rear surface which joins the cone smoothly. Now a will denote the radius of the rear surface. In this case specularly reflected rays are returned to the source for all values of ϕ in the range $\frac{\pi}{2} - \gamma \leq \phi \leq \pi$. In the range $0 \leq \phi < \frac{\pi}{2} - \gamma$ only tip and surface diffracted rays return to the source. When $\phi = 0$ the surface diffracted rays have a caustic on the axis so their field there is multiplied by $k^{1/2}$. The relative importance of these two kinds of rays depends upon the value of ka. For very large values of ka, the tip ray is more important while for smaller values of ka the surface rays are dominant. When the tip ray is dominant, interference does not occur, so the field does not oscillate as ka varies.

3. Flat based cone - single diffraction

We shall first determine the back scattered field for the flat-based cone when $\phi \neq 0, \frac{\pi}{2} - \gamma, \pi$. The field on rays singly diffracted from the edge will be called u_{e1}. According to reference [2], it is given by

$$(1) \qquad u_{e1}(P) = \left[r_1(1+\rho_1^{-1}r_1)\right]^{-1/2} e^{ikr_1} D_1 u_i(P_1) + \left[r_2(1+\rho_2^{-1}r_2)\right]^{-1/2} e^{ikr_2} D_2 u_i(P_2).$$

In (1), P denotes the point at which the field is being determined while P_1 and P_2 denote the two points on the edge from which rays are diffracted to P. The point on the edge nearest to P is P_1 and its distance from P is r_1.

D_1 is the diffraction coefficient which depends upon the directions of the incident and diffracted rays at P_1. The non-vanishing radius of curvature of the diffracted wavefront at P_1 is ρ_1, and the incident field is u_i. The corresponding quantities with the subscript '2' are evaluated at P_2, the point on the edge farthest from P. When ϕ lies in the range $\gamma < \phi < \frac{\pi}{2}$ only the P_1 term is present in (1) since then the point P_2 is hidden by the cone.

To evaluate the right side of (1) let us introduce the polar coordinates r, θ. In terms of them the incident field is assumed to be given by

$$u_i(r,\theta) = A\, e^{-ikr\cos(\theta-\phi)}. \tag{2}$$

In (2) A is a constant, which is a vector in the electromagnetic case. The coordinates of P_1 are a csc γ and $\pi-\gamma$ so $u_i(P_1) = A\exp\left[ika\csc\gamma\cos(\gamma+\phi)\right]$. Similarly $u_i(P_2) = A\exp\left[ika\csc\gamma\cos(\gamma-\phi)\right]$. The radius ρ_1 is just the signed distance along the diffracted ray from P_1 to the axis, which is a caustic of the diffracted rays. A simple geometrical calculation yields

$$(1+\rho_1^{-1}r_1) = \frac{r\sin\theta}{a} \tag{3}$$

$$(1+\rho_2^{-1}r_2) = \frac{-r\sin\theta}{a} . \tag{4}$$

To calculate D_1 for an acoustic wave we utilize (A10) of reference [2].* In that equation we must set $\beta = \pi/2$ because the incident ray is normally incident on the edge. We also set $\theta = \alpha$ because we will consider only back scattering. We find at once that at P_1, $\alpha = \pi - \phi$ while at P_2, $\alpha = \pi + \phi$. Thus we obtain

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*Equation (A10) of reference [2] is written incorrectly and should read

$$D = \frac{e^{i\pi/4}\sin(\pi/n)}{n\,\sin\beta\sqrt{2\pi k}}\left[\left(\cos\frac{\pi}{n} - \cos\frac{\theta-\alpha}{n}\right)^{-1} \mp \left(\cos\frac{\pi}{n} - \cos\frac{\theta+\alpha+\pi}{n}\right)^{-1}\right].$$

$$(5) \qquad D_1 = \frac{e^{i\pi/4}\sin(\pi/n)}{n\sqrt{2\pi k}}\left[\left(\cos\frac{\pi}{n}-1\right)^{-1} \mp \left(\cos\frac{\pi}{n}-\cos\frac{3\pi-2\phi}{n}\right)^{-1}\right].$$

Here $n = \frac{3}{2} + \frac{\gamma}{\pi}$. The upper sign in (5) applies to the cone on which the field vanishes (the soft cone) while the lower sign applies to one on which the normal derivative vanishes (the hard cone). To obtain D_2 we need merely change the sign of ϕ in (5). In the electromagnetic case these same diffraction coefficients can be used, the upper sign applying to the electric field component parallel to the edge and the lower sign to the component normal to the edge.

For large r it is convenient to express r_1 and r_2 in the phase factors in terms of r and θ by $r_1 \approx r + a \csc\gamma \cos(\gamma+\phi)$ and $r_2 \approx r + a \csc\gamma \cos(\gamma-\phi)$. In the amplitudes it suffices to use $r_1 \approx r_2 \approx r$. Upon combining all these results, and setting $\theta = \phi$, we obtain from (1) in the scalar case

$$(6) \quad u_{el}(r,\phi) = \frac{\sqrt{a}\,\sin(\pi/n)Ae^{ikr+2ka\csc\gamma\cos(\gamma+\phi)+i\frac{\pi}{4}}}{nr\sqrt{2\pi k\sin\phi}}\left[\left(\cos\frac{\pi}{n}-1\right)^{-1} \mp \left(\cos\frac{\pi}{n}-\cos\frac{3\pi-2\phi}{n}\right)^{-1}\right].$$

This result holds for $\gamma < \phi < \frac{\pi}{2}$ when only one edge diffracted ray returns to the source. In the range $0 < \phi < \gamma$ and $\frac{\pi}{2} < \phi < \pi$ when two such rays occur, u_{el} is given by the right side of (6) plus the same expression with ϕ replaced by $-\phi$. Thus in this range

$$(7) \quad u_{el}(r,\phi) = \frac{\sqrt{a}\,\sin(\pi/n)Ae^{ikr}}{nr\sqrt{2\pi k\sin\phi}}\left\{e^{i\left[2ka\csc\gamma\cos(\gamma+\phi)+\frac{\pi}{4}\right]}\left[\left(\cos\frac{\pi}{n}-1\right)^{-1} \mp \left(\cos\frac{\pi}{n}-\cos\frac{3\pi-2\phi}{n}\right)^{-1}\right]\right.$$

$$\left. + e^{i\left[2ka\csc\gamma\cos(\gamma-\phi)-\frac{\pi}{4}\right]}\left[\left(\cos\frac{\pi}{n}-1\right)^{-1} \mp \left(\cos\frac{\pi}{n}-\cos\frac{3\pi+2\phi}{n}\right)^{-1}\right]\right.$$

(In the last term $3\pi+2\phi$ must be replaced by $2\phi-\pi$ when $\frac{\pi}{2} \leq \phi \leq \pi$.) In (6) and (7) the upper signs hold for the soft cone and the lower signs for the hard cone.

In the electromagnetic case (6) and (7) also apply. The soft cone result applies to the electric field component parallel to the edge at P_1 - i.e., perpendicular to the plane containing P and the axis. The hard cone result applies to the electric field component normal to the edge at P_1 - i.e., lying in the plane containing P and the axis.

The result (6) is not valid at $\phi = \frac{\pi}{2} - \gamma$ where it becomes infinite. For this value of ϕ the specularly reflected ray must also be taken into account. The result (7) is not valid at $\phi = 0, \pi$ where it becomes infinite. For these values of ϕ the diffracted rays form a caustic on the axis, and in addition at $\phi = \pi$ the specularly reflected rays must be considered.

Let us first obtain a modified form of (7) valid at $\phi = 0$. To this end we define $\rho = r \sin\theta$, which is the distance of P from the axis. We also define $\delta = \cos^{-1}(a/r)$ and note that $\rho \cos\delta = a \sin\theta$. Now we must reexamine (7) before setting θ equal to ϕ, with $\phi = 0$. Therefore we return to (1), set $u_i(P_1) = u_i(P_2)$ and $D_1 = D_2$, use (3) and (4), and in the phase set $r_1 = (r\cos\theta + a\cot\gamma)\sin\delta + (a - \rho)\cos\delta$. For r_2 we use the same formula with $-\rho$ in place of ρ. Then (1) becomes, after some simplification, instead of (7)

$$(8) \qquad u_{el}(r,\theta) = \frac{a\sin(\pi/n)Ae^{2ika\cot\gamma}}{nr\sqrt{2\pi k\rho\cos\delta}} \left[(\cos\frac{\pi}{n} - 1)^{-1} \mp (\cos\frac{\pi}{n} - \cos\frac{3\pi}{n})^{-1}\right]$$

$$\left[e^{ik(r\cos\theta\sin\delta-\rho\cos\delta)+i\frac{\pi}{4}} + e^{ik(r\cos\theta\sin\delta+\rho\cos\delta)-i\frac{\pi}{4}}\right].$$

This is of the form given in (A15) of reference [2]. Therefore we may

apply the axial caustic correction given there. Upon doing so and eliminating δ, we obtain for θ small

$$(9) \quad u_{el}(r,\theta) = \frac{a\sin(\pi/n)Ae^{ik(r+2a\cot\gamma)}}{nr} J_o(ka\sin\theta)\left[(\cos\frac{\pi}{n}-1)^{-1} \mp (\cos\frac{\pi}{n}-\cos\frac{3\pi}{n})^{-1}\right].$$

At $\theta = 0$, the Bessel function J_o is equal to one. Thus at $\theta = 0$ (9) becomes the following, which is the back scattered field at $\phi = 0$

$$(10) \quad u_{el}(r,0) = \frac{a\sin(\pi/n)Ae^{ik(r+2a\cot\gamma)}}{nr}\left[(\cos\frac{\pi}{n}-1)^{-1} \mp (\cos\frac{\pi}{n}-\cos\frac{3\pi}{n})^{-1}\right].$$

Now we consider $\phi = \pi$. Again we must return to (1) and keep $\theta \neq \pi$. Proceeding as above we obtain from (1)

$$(11) \quad u_{el}(r,\theta) = \frac{a\sin(\pi/n)Ae^{-2ika\cot\gamma}}{nr\sqrt{2\pi k\rho\cos\delta}}\left[(\cos\frac{\pi}{n}-1)^{-1} \mp (\cos\frac{\pi}{n}-\cos(\frac{\pi}{2n}+\frac{\delta}{n}))^{-1}\right]$$

$$\left[e^{ik(-r\cos\theta\sin\delta+[a-\rho]\cos\delta)+i\frac{\pi}{4}} + e^{ik(-r\cos\theta\sin\delta+[a+\rho]\cos\delta-i\frac{\pi}{4}}\right].$$

Upon applying the caustic correction to (11), we obtain

$$(12) \quad u_{el}(r,\theta) = \frac{a\sin(\pi/n)Ae^{-ik(r\cos\theta\sin\delta+2a\cot\gamma)}}{nr} J_o(ka\sin\theta)\left[(\cos\frac{\pi}{n}-1)^{-1}\right.$$

$$\left. \mp(\cos\frac{\pi}{n}-\cos(\frac{\pi}{2n}+\frac{\delta}{n}))^{-1}\right].$$

Although (12) is finite at any finite distance r along the axis, it becomes infinite as r becomes infinite because then $\delta = \cos^{-1}(a/r)$ tends to $\pi/2$. Of course there is also a reflected field u_R on and near the axis, given by

$$(13) \quad u_R(r,\theta) = \mp Ae^{-ik(r\cos\theta+2a\cot\gamma)}, \qquad |r\sin\theta| < a, \qquad \theta > \frac{\pi}{2}.$$

The total field (u,r,θ) is the sum of the reflected and diffracted fields. Its form on the axis for large r can be computed from (12) and (13) by first setting $\theta = \pi$ and $\delta = (\pi/2) - (a/r)$. Then for large r,

$$(14) \quad u = u_R + u_{el} = Ae^{ik(r-2a\cot\gamma)}\left[\mp 1 \mp \frac{a\sin(\pi/n)}{nr}\left(1-\frac{ika^2}{2r}\right)\left(\cos\frac{\pi}{n} - \cos\left(\frac{\pi}{n} - \frac{a}{nr}\right)\right)^{-1}\right]$$

$$= \mp \frac{ika^2A}{2r}\, e^{ik(r - 2a\cot\gamma)} \,.$$

Equations (6), (7), (10) and (14) give the back-scattered field for all directions of incidence except $\phi = \pi/2 - \gamma$. From these equations we can compute the back scattering cross section $\sigma(\phi) = 4\pi r^2|u|^2|A|^{-2}$. We obtain for the scalar cases (upper sign for soft cone, lower sign for hard cone)

$$(15) \quad \frac{\sigma(0)}{\pi a^2} = \frac{4}{n^2}\sin^2\frac{\pi}{n}\left[\left(\cos\frac{\pi}{n} - 1\right)^{-1} \mp \left(\cos\frac{\pi}{n} - \cos\frac{3\pi}{n}\right)^{-1}\right]^2$$

$$(16) \quad \frac{\sigma(\pi)}{\pi a^2} = (ka)^2$$

$$(17) \quad \frac{\sigma(\phi)}{\pi a^2} = \frac{2\sin^2(\pi/n)}{n^2\pi ka\sin\phi}\left[\left(\cos\frac{\pi}{n} - 1\right)^{-1} \mp \left(\cos\frac{\pi}{n} - \cos\frac{3\pi - 2\phi}{n}\right)^{-1}\right]^2 \qquad \gamma < \phi < \frac{\pi}{2}$$

$$(18) \quad \frac{\sigma(\phi)}{\pi a^2} = \frac{2\sin^2(\pi/n)}{n^2\pi ka\sin\phi}\left|e^{-i(2ka\sin\phi - \pi/4)}\left[\left(\cos\frac{\pi}{n} - 1\right)^{-1} \mp \left(\cos\frac{\pi}{n} - \cos\frac{3\pi - 2\phi}{n}\right)^{-1}\right]\right.$$

$$\left. + e^{i(2ka\sin\phi - \pi/4)}\left[\left(\cos\frac{\pi}{n} - 1\right)^{-1} \mp \left(\cos\frac{\pi}{n} - \cos\frac{3\pi + 2\phi}{n}\right)^{-1}\right]\right|^2, \quad 0 < \phi < \gamma$$

$$(19)\quad \frac{\sigma(\phi)}{\pi a^2} = \frac{2\sin^2(\pi/n)}{n^2\pi\, ka\sin\phi}\left| e^{-i(2ka\sin\phi - \pi/4)}\left[(\cos\frac{\pi}{n}-1)^{-1} \mp \left(\cos\frac{\pi}{n} - \cos\frac{3\pi - 2\phi}{n}\right)^{-1}\right]\right.$$

$$\left. + e^{i(2ka\sin\phi - \pi/4)}\left[(\cos\frac{\pi}{n}-1)^{-1} \mp \left(\cos\frac{\pi}{n} - \cos\frac{2\phi - \pi}{n}\right)^{-1}\right]\right|^2, \quad \frac{\pi}{2} < \phi < \pi$$

Equations (10) and (15) are not valid when $\gamma = \pi/2$, in which case the cone becomes a circular disk. In that case the right side of (10) must be replaced by that of (14) and that of (15) by the right side of (16).

In the electromagnetic case when $\phi \neq 0, \pi$ we may define the plane Γ containing the axis of the cone and the source (or an incident ray). Let us suppose that the incident wave is linearly polarized and that the incident electric field makes the angle Ψ with the normal to this plane. Then the component of the incident field normal to the edge at the points of diffraction is proportional to $\sin\Psi$ and that parallel to the edge is proportional to $\cos\Psi$. Thus the back scattered field component normal to the plane Γ is given by $u^S_{el}(r,\phi)\cos\Psi$ and that parallel to the plane Γ is $u^H_{el}(r,\phi)\sin\Psi$. Here u^S_{el} and u^H_{el} are the back scattered scalar fields. The superscript S refers to the soft cone and H to the hard cone. From these results we find that the back scattering cross section σ_{EM} for the electromagnetic case is given by

$$(20)\quad \sigma_{EM}(\phi) = \sigma_S(\phi)\cos^2\Psi + \sigma_H(\phi)\sin^2\Psi \qquad \phi \neq 0, \pi \quad .$$

For axial incidence $\phi = o, \pi$ the back scattered field $\vec{E}$ is given by

$$(21) \qquad \vec{E} = \frac{1}{2}(u^S - u^H)\,\vec{E}_i \,.$$

Here $\vec{E}_i$ is the incident field at the body while u^S and u^H denote the scalar back-scattered fields, which may be reflected, diffracted from edges, or diffracted around curved surfaces. The relation (21) holds for back scattering along the axis of any body of revolution. It can be proved by considering the fields on the various rays.[14] Upon combining (21) with (10) we obtain

$$(22) \qquad \frac{\sigma_{EM}(0)}{\pi a^2} = \frac{4\sin^2(\pi/n)}{n^2}\left(\cos\frac{\pi}{n} - \cos\frac{3\pi}{n}\right)^{-2}$$

Graphs of $\sigma(0)$ versus γ, based on (22) and (15), are shown in Figure 3. From (21) and (14) we find

$$(23) \qquad \frac{\sigma_{EM}(\pi)}{\pi a^2} = (ka)^2$$

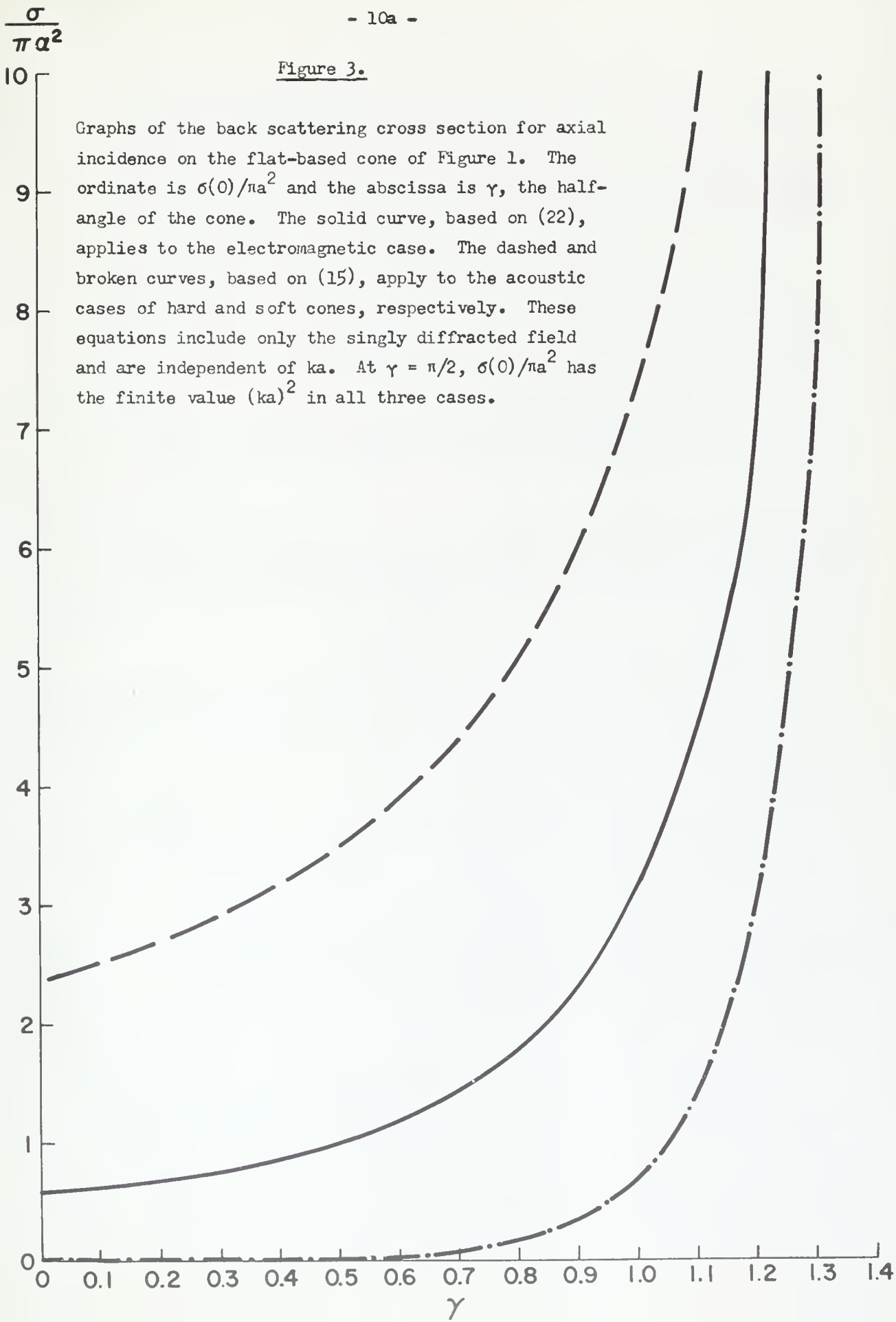
As in the scalar case, when $\gamma = \pi/2$ and the cone is a disk, the right side of (22) must be replaced by that of (23).

4. <u>Flat based cone - double diffraction.</u>

Some of the singly diffracted rays produced by the incident ray traverse the base of the cone, hit the opposite edge and produce doubly diffracted rays. Some of these rays return to the source, contributing

Figure 3.

Graphs of the back scattering cross section for axial incidence on the flat-based cone of Figure 1. The ordinate is $\sigma(0)/\pi a^2$ and the abscissa is γ, the half-angle of the cone. The solid curve, based on (22), applies to the electromagnetic case. The dashed and broken curves, based on (15), apply to the acoustic cases of hard and soft cones, respectively. These equations include only the singly diffracted field and are independent of ka. At $\gamma = \pi/2$, $\sigma(0)/\pi a^2$ has the finite value $(ka)^2$ in all three cases.



to the back scattering. We shall now analyze this effect in the case of axial incidence upon the tip of the cone since in this case the effect of double diffraction is greater than that of tip diffraction.

The field on a ray singly diffracted at P_1 is given by the first term on the right side of (1). For a ray traversing the base of the cone $\rho_1 = -a$ and the diffraction coefficient D_1 is given by

$$(24) \qquad D = \frac{e^{i\pi/4}\sin(\pi/n)}{n\,(2\pi k)^{1/2}}\left[\left(\cos\frac{\pi}{n} - \cos\frac{3\pi}{2n}\right)^{-1} \mp \left(\cos\frac{\pi}{n} - \cos\frac{3\pi}{2n}\right)^{-1}\right].$$

For the soft cone (24) shows that $D = 0$. This ray reaches the point P_2 on the opposite edge when $r_1 = 2a$. The field on this ray at P_2 is

$$(25) \qquad u_{e1}(P_2) = D(2a)^{-1/2}\, e^{2ika - i\pi/2}\, u_i(P_1) .$$

Similarly the field $u_{e1}(P_1)$ on a ray produced at P_2 is given by the right side of (25) with $u_i(P_1)$ replaced by $u_i(P_2)$, but with the same diffraction coefficient.

The field (25) may be considered to be the incident field which gives rise to a doubly diffracted ray. The doubly diffracted field $u_{e2}(P)$ at a point P which is near, but not on the axis will consist of two terms like those in (1), since two doubly diffracted rays pass through P. One of these comes from P_1 and another comes from P_2. Thus we have

$$(26) \qquad u_{e2}(P) = \left[r_1(1+\rho_1^{-1}r_1)\right]^{-1/2} e^{ikr_1}\, D_3 u_{e1}(P_1) + \left[r_2(1+\rho_1^{-1}r_2)\right]^{-1/2} e^{ikr_2}\, D_4\, u_{e1}(P_2) .$$

If the point P is far from the cone and near the axis, D_3 and D_4 are both equal to D which is given by (25).

We now proceed to simplify (26) exactly as we did in obtaining (10) from (1). In fact, by comparing (1) and (26) we see that they differ only by the factor $D_3 u_{e1}(P_1)/D_1 u_i(P_1)$. This is so because for $\phi = 0, u_{e1}(P_1) = u_{e2}(P_2)$. Furthermore, for P far from the cone and near the axis, D_1 and D_2 are equal just as D_3 and D_4 are. As a consequence we can obtain the simplified form of (26) by multiplying (10) by the factor given above. Since $u_{e1}(P_1)$ as given by (25) contains $u_i(P_1)$, the factor becomes $D^2(2a)^{-1/2}\, e^{2ika-i\pi/2}(D_1)^{-1}$. In this way we obtain for the hard cone

$$(27) \qquad u^H_{e2}(r,0) = \frac{2\sin^2(\pi/n)\, a^{1/2}\, Ae^{ikr} e^{2ika(\cot\gamma + 1) - i\pi/4}}{n^2\, (\pi k)^{1/2}\, r} \left(\cos\frac{\pi}{n} - \cos\frac{3\pi}{2n}\right)^{-2}.$$

For the soft cone D = 0 and therefore

$$(28) \qquad u^S_{e2}(r,0) = 0 \ .$$

Let us now combine the singly and doubly diffracted back scattered fields. For the hard cone (10) and (27) yield

$$(29) \qquad u^H_{e1}(r,0) + u^H_{e2}(r,0) = \frac{aA\sin(\pi/n)e^{ik(r + 2a\cot\gamma)}}{nr} \left[\left(\cos\frac{\pi}{n} - 1\right)^{-1} + \left(\cos\frac{\pi}{n} - \cos\frac{3\pi}{2n}\right)^{-1}\right.$$

$$\left. + \frac{2\sin(\pi/n)e^{2ika - i\pi/4}}{n\,(\pi ka)^{1/2}} \left(\cos\frac{\pi}{n} - \cos\frac{3\pi}{2n}\right)^{-2}\right].$$

The back scattering cross section $\sigma_H(0)$ is now $4\pi r^2 A^{-2}$ multiplied by the square of the absolute value of the right hand side in (29). For the soft cone (10) and (15) still apply since $u^S_{e2}(r,0) = 0$.

For the electromagnetic case we insert (10) for u^S and (29) for u^H into (21). Then if $\vec{A}$ denotes the vector amplitude of the incident field at the cone, we obtain

$$(30)\quad \vec{E}_{e1}(r,0) + \vec{E}_{e2}(r,0) = -\frac{a\vec{A}\sin(\pi/n)\, e^{ik(r + 2a\cot\gamma)}}{nr}\left[\left(\cos\frac{\pi}{n} - \cos\frac{3\pi}{n}\right)^{-1} + \frac{\sin(\pi/n)\, e^{2ika - i\pi/4}}{n(\pi ka)^{1/2}}\left(\cos\frac{\pi}{n} - \cos\frac{3\pi}{2n}\right)^{-2}\right] .$$

The back scattering cross section $\sigma_{EM}(0)$ is $4\pi r^2|\vec{A}|^{-2}$ multiplied by the square of the absolute value of the right hand side in (30). Graphs of $\sigma(0)$ versus ka, based on (29) and (30), are shown in Figure 4.

5. Cone with a spherical base

Let us now consider back scattering from the cone of Figure 2. When the direction of incidence lies in the range $\pi/2 - \gamma < \phi \leq \pi$ some incident ray hits the cone normally and is reflected back to the source. The back scattering cross section for such directions is then given by the well-known geometrical optica formula

$$(31)\qquad \sigma_S = \sigma_H = \sigma_{EM} = \pi a^2 \qquad\qquad \pi/2 - \gamma < \phi \leq \pi .$$

When the direction of incidence lies in the range $0 \leq \phi < \pi/2 - \gamma$, only a tip diffracted ray and one or more surface diffracted rays return to the source. In the range $0 \leq \phi \leq \gamma$ infinitely many surface diffracted rays return to the source, and they form an axial caustic extending in the direction of the source. The field on this caustic is the same as the diffracted part of the back-scattered field from a sphere, if rays which make complete revolutions around the sphere are excluded. The latter field is given in reference [15] equations (95) and (96). If we add this field to that on the tip

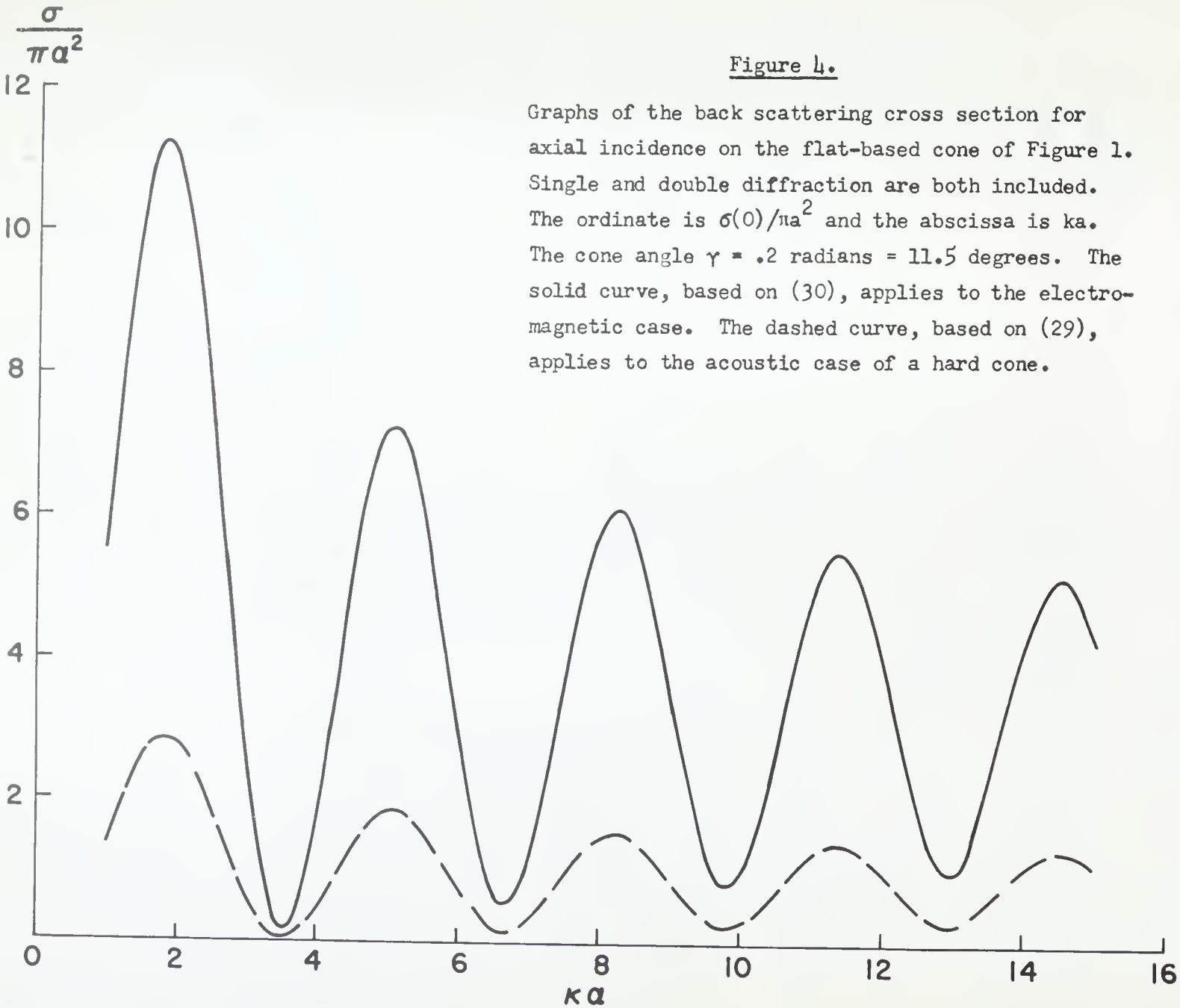


Figure 4.

Graphs of the back scattering cross section for axial incidence on the flat-based cone of Figure 1. Single and double diffraction are both included. The ordinate is $\sigma(0)/\pi a^2$ and the abscissa is ka. The cone angle γ = .2 radians = 11.5 degrees. The solid curve, based on (30), applies to the electromagnetic case. The dashed curve, based on (29), applies to the acoustic case of a hard cone.

diffracted ray we obtain in the scalar case

$$(32)\quad u(r,\phi) = \frac{aAe^{ikr}}{2r}\left[2C(\phi)(ka)^{-1} + G(ka)^{1/3}\, e^{-\tau(ka)^{1/3}}\, e^{ika(\pi+2\csc\gamma\cos\phi)}\right],\ 0 \le \phi \le \gamma\ .$$

In (32) $C(\phi)$ is the tip diffraction coefficient for back scattering which depends upon ϕ and upon whether the cone is soft or hard. The constants G and τ are also different in the two cases and are given by

$$(33)\quad G_S = -4\pi^2 6^{-4/3}\left[A'(q_S)\right]^{-2} e^{i\pi/3}\ ,\quad \tau_S = e^{-i\pi/6}\, 6^{-1/3}\, q_S\pi,\quad A(q_S) = 0 \quad \text{SOFT CONE}$$

$$(34)\quad G_H = -2\pi^2 6^{-1/3} q_H^{-1}\left[A(q_H)\right]^{-2} e^{i\pi/3},\quad \tau_H = e^{-i\pi/6}\, 6^{-1/3}\, q_H\pi,\ A'(q_H) = 0 \quad \text{HARD CONE}$$

In these equations the subscripts S and H refer to the soft and hard cones. The function $A(q)$ is the Airy function. The roots q_S and q_H are given in reference [15]. The tip diffraction coefficient has been determined by L. B. Felsen and the others referred to in the introduction.

In the electromagnetic case we may use (21) to obtain the contribution to $\vec{E}$ from surface diffracted rays in the range $0 \le \phi \le \gamma$. This is so because for these rays in this range the rear hemisphere accounts for the back scattering, and it is axially symmetric about any axis in this range. The field back scattered from the tip must be computed with the aid of the tip diffraction coefficient matrix which we will also denote by $C(\phi)$. Thus we have

$$(35)\quad \vec{E}(r,\phi) = \frac{a}{2r}\, e^{ikr}\left[2(ka)^{-1}C(\phi) + \frac{(ka)^{1/3}}{2}\, e^{ika(\pi+2\csc\gamma\cos\phi)} \times \left(G_S e^{-\tau_S(ka)^{1/3}} - G_H e^{-\tau_H(ka)^{1/3}}\right)\right]\vec{E}_i\quad ,\ 0 \le \phi \le \gamma$$

This result can be simplified by omitting the term $G_S \exp\left[-\tau_S (ka)^{1/3}\right]$ since it is much smaller than the term $G_H \exp\left[-\tau_H (ka)^{1/3}\right]$.

6. Conclusion.

On the basis of the preceding considerations it is possible to draw some conclusions about shaping an object to minimize its back-scattering cross section σ. These conclusions are

a) The object should not have any flat, cylindrical or conical surfaces which might be hit normally by an incident wave. Such surfaces can only be hit normally from a narrow range of directions. Although they yield very strong reflections within this range, they yield correspondingly small return in all other directions. For example an object with an ogival nose instead of a conical one yields a smaller reflection when it is hit normally, but it can be hit normally from a greater range of directions. The decision about whether to include flat, cylindrical or conical surfaces and thus permit big reflections in a small range of directions and very little in other directions, or to exclude them and use only doubly curved surfaces which yield a somewhat smaller reflection over a larger range of directions, must be based on operational considerations.

If only a limited range of directions of incidence need be considered then:

b) The object should have no surface which can be hit normally from the range of incidence directions under consideration. This is the case for a finite cone when the incidence directions are confined to the neighborhood of the axis.

c) If the object does have a surface which can be hit normally, that surface should be as curved as possible. Thus if the object is a cone with a rounded tip and if the incidence directions are nearly axial, the tip should

have as small a radius as possible.

d) The object should have no edge which can be hit normally by an incident ray. Thus if the object is a finite cone with a flat or curved rear surface, the conical and rear surfaces should join smoothly and not meet at a sharp edge. Whether a sharply curved surface behaves as an edge or not depends upon the relative sizes of its radius of curvature and the wavelength. The larger the radius compared to the wavelength, the less the surface behaves like an edge. Of course rounding off such an edge diminishes the back-scattering from axial and nearly axial directions, but it increases back-scattering in certain directions near the rear from which reflection from the round edge now becomes possible.

Suppose the object is a finite cone with incidence directions which are nearly axial. Then

e) It should have a rounded rather than a flat rear surface. This diminishes the contribution of the surface rays which traverse the rear surface.

f) The rear surface should not be axially symmetric. This will eliminate the caustic of the diffracted rays on the axis, in the case of axial incidence. Thus it will significantly cut down the cross section for such incidence.

g) The rear surface should probably have some sharp edges or conical tips. This will help to interrupt the surface rays on the rear surface and cause them to radiate most of their energy away from the surface.

Suggestions similar to some of these have been made by S. Silver and by K.M. Siegel.

References

[1] Keller, J.B. - A geometrical theory of diffraction, Calculus of Variations and Its Applications, Proc. of Symp. in Appl. Math. Vol. 8, pp. 27-52, Mc Graw-Hill, New York 1958.

[2] - Jour. App. Phys. 28, 426-444 (1957).

[3] Carslaw, H.S. Math. Ann. 75, 133-147 (1914).

[4] Hansen, W.W. and Schiff, L.I. Microwave Laboratory, Stanford Univ., Quarterly Reports 1,2,3,4, Nov. 1947 - Sept. 1948, Contract W28-099-333.

[5] Schensted, C.E. Application of summation techniques to the radar cross-section of a cone, Symposium on Microwave Optics, Mc Gill Univ., Montreal, Canada, June 1953.

[6] Siegel, K.M., Crispin, J.W. and Schensted, C.E. Jour. App. Phys. 26, 309-313 (1955).

[7] Felsen, L.B. Back scattering from wide-angle and narrow-angle cones, Symposium on Microwave Optics, Mc Gill Univ., Montreal, Canada, June 1953.

[8] - Jour. App. Phys. 26, 138-151 (1955).

[9] - IRE Transactions PGAP Vol. AP-5, 121-129 (1957).

[10] - Back scattering from a semi-infinite cone, Microwave Research Inst., Polytechnic Inst. of Brooklyn, Memo. 43, R-675-58, PIB-603, July 1958.

[11] Spencer, R.C. Back scattering from conducting surfaces, Air Force Cambridge Research Laboratories, Report CRL-E5070, April 1951.

[12] Siegel, K.M., Alperin, H.A., Bonkowski, R.R., Crispin, J.W., Moffett, A.L., Schensted, C.E. and Schensted, I.V. Jour. App. Phys. 26, 297-305 (1955)

[13] Siegel, K.W. Far field scattering from bodies of revolution; URSI 12th General Assembly, Boulder, Colorado (1957).

[14] Levy, B.R. and Keller, J.B. Diffraction by a spheroid; N.Y.U., Inst. Math. Sci., Div. EM Research, Report No. EM-130, April, 1959.

[15] - Comm. Pure and Appl. Math.; 12, 159 (1959).

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